CONTROL STRATEGIES FOR COUPLING THERMAL ENERGY STORAGE SYSTEMS WITH SMALL MODULAR REACTORS

Konor Frick and Dr. J. Michael Doster
Department of Nuclear Engineering
North Carolina State University
2500 Stinson Drive
3105 Burlington Engineering Labs
Raleigh, NC, 27695-7909
klfrick2@ncsu.edu; doster@ncsu.edu

Dr. Shannon M. Bragg-Sitton
Nuclear Science and Technology
Idaho National Laboratory
Shannon.Bragg-Sitton@inl.gov

ABSTRACT

The contribution of intermittent (renewable) energy sources such as wind and solar continues to increase as renewables improve in both efficiency and price-point. However, the variability of renewables generates additional challenges for the electric grid in the form of rapidly varying electric loads.

Proposed options for accommodating this load have included operating nuclear reactors in a load follow mode, or operating the reactor at or near steady state and bypassing steam directly to the condenser. Both of these strategies result in lost energy potential. In addition to lost energy potential, load follow operation can result in increased stress on the fuel and other mechanical components. A more attractive approach is to operate the reactor at or near steady state and bypass excess steam to a thermal energy storage system. The thermal energy can then be recovered, either for electric generation during periods of peak electric demand, or for use in ancillary applications such as desalination and hydrogen production.

Sensible Heat Thermal Energy Storage is a mature technology currently used in solar energy systems. This research focuses on the design and coupling of such a system to Small Modular Reactors (SMRs), typical of Integral Pressurized Water Reactor (IPWR) designs currently under development.

1 INTRODUCTION

Thermal energy storage has been proposed as a load management strategy for Small Modular Reactors (SMRs) deployed on constrained grids and/or in hybrid energy systems [1]. Hybrid energy systems can include process steam applications, and the presence of intermittent energy sources such as wind and solar. Under these conditions, the reactor can be subjected to significant time varying electric loads. Options for accommodating this load have included operating nuclear reactors in a load follow mode, or operating the reactor at or near steady state and bypassing steam directly to the condenser [2]. Both of these strategies result in lost energy potential. Load follow operation can also result in additional stresses on the fuel and other mechanical components. A more attractive approach is to operate the reactor at or near steady state and bypass excess steam to a thermal energy storage system. The thermal energy can then be recovered, either as a supplement to the power plant during peak demand times, or can be used for other ancillary applications [1]. Sensible heat thermal energy storage systems have been demonstrated in solar energy systems [3]. This paper describes the benefits of applying such a system to SMRs.

1.1 Design of Thermal Energy Storage System

The proposed Thermal Energy Storage (TES) System is shown in Figure 1. An outer loop interfaces with the reactor's Balance of Plant (BOP) directly through four parallel auxiliary turbine bypass valves connected at the pressure equalization header, each staged to open at a certain percent of the maximum auxiliary flow demand. Bypass steam is directed through an intermediate heat exchanger (IHX) and discharged to the main condenser. An inner loop containing a TES fluid consists of two large storage tanks along with several pumps to transport the TES fluid between the tanks, the IHX and a steam generator. Flow Bypass Valves are included in the discharge lines of both the Hot and Cold tanks to prevent deadheading the pumps when the Flow Control Valves are closed. Common TES fluid properties are given in Table I. Therminol-66 is chosen as the TES fluid in this work as it is readily available, can be pumped at low temperatures, and offers thermal stability over the range (-3°C - 343°C) which covers the anticipated operating range of the TES system (176°C - 260°C).

Table I: Properties of Possible TES fluids at ~260 degrees Celsius (500 degrees Fahrenheit)

Heat Transfer Fluid	Boiling Point (°C)	Heat Storage (W*hr/m^3°C)	Operating Range (°C)
Therminol®-66 [4]	358 (678 F)	1039 (576.95 W*hr/m^3°F)	-2.7-343.3 (27 F-650 F)
Therminol®-68 [5]	307 (586 F)	1013 (563.03 W*hr/m^3°F)	-25.5 – 360 (-14 F-680 F)
Therminol®-75 [6]	342 (649 F)	992 (551.54 W*hr/m^3°F)	79.44 – 385 (175 F-725 F)

The TES system is designed to allow the reactor to run continuously at ~100% power over a wide range of operating conditions. System parameters for an mPower [7] size system are given in Table II. During periods of excess capacity, bypass steam is directed to the TES unit through the auxiliary bypass valves where it condenses on the shell side of the IHX. TES fluid is pumped from the Cold Tank to the Hot Tank through the tube side of the IHX at a rate sufficient to raise the temperature of the TES fluid to some set point. Condensate is collected in a hot well below the IHX and drains back to the main condenser. The TES fluid is then stored in the Hot Tank at constant temperature. The system is discharged during periods of peak demand, or when process steam is desired, by pumping the TES fluid from the Hot Tank through a boiler (steam generator) to the Cold Tank. This process steam can then be reintroduced into the power conversion cycle for electricity production or directed to some other application. While the boiler in Figure 1 implies a Once Through Steam Generator (OTSG) design, a U-Tube design could just as easily be substituted. Although it is not indicated in Figure 1, pressure relief lines connect the shell side of the IHX with the condenser to prevent over pressurization of the heat exchanger during periods of low condensation rate. A nitrogen cover gas dictates the tank pressures during charging and discharging operation. For the purposes of this paper we will focus on the control strategies required of the charging mode when deployed in conjunction with an IPWR system. In previous work, details on the equation sets and solution strategy used for solving the standalone charging system have been provided [8].

Table II: TES Design Parameters for connection with an mPower size IPWR

Parameter	Value
TES Fluid	Therminol®-66
Hot tank Volume	226,535 m^3
Cold Tank Volume	226,535 m^3
IHX reference Exit Temperature	260 $^\circ$C (500°F)
Number of TBV’s	4
TES maximum steam accommodation	~45% Nominal
Pressure Relief Valve Upper Setpoint	5.377 MPa (780 psi)
Pressure Relief valve Lower Setpoint	5.240 MPa (760 psi)
Turbine Header Pressure	5.688 MPa (825 psi)
Shell Side (outer loop) IHX Volume	33.159 m^3 (1171 ft^3)
Number of tubes	19140
Length of tubes	11.247 m (36.9ft)
Tube Inner Diameter	0.013 m (0.044ft)
Tube Outer Diameter	0.018 m (0.058 ft)
Mass of Hot Tank Fill Gas	2.375x10^5 kg (5.235x10^5 lbm)
Mass of Cold Tank Fill Gas	2.036x10^5 kg (4.489x10^5 lbm)

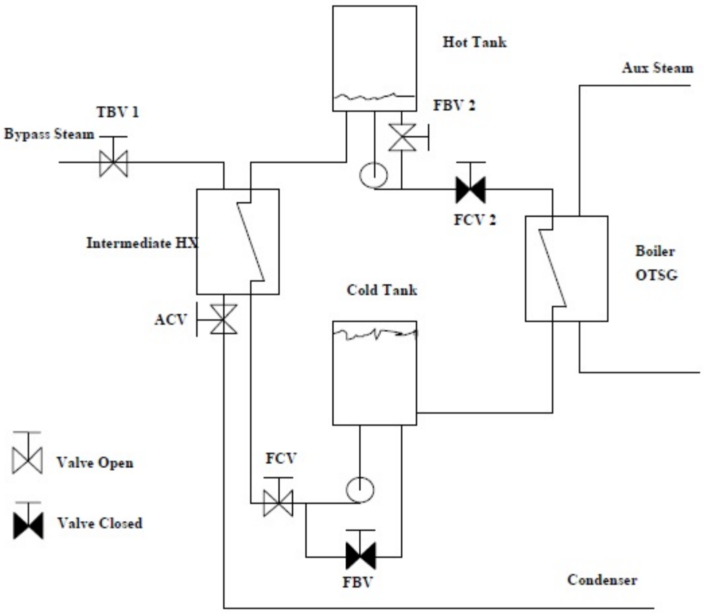

Figure 1: Thermal Energy Storage System (charging mode).

1.2 SMR Configuration

The target SMR in this work is an IPWR with operating parameters similar to those of the mPower reactor being developed by B&W [7]. Operating parameters are given in Table III. The steam generators are a typical once through design, with steam generator pressure control via the turbine control valves (TCVs) located between the pressure equalization header and the high pressure turbine. In order to simulate the dynamics of an IPWR system, NCSU has developed high fidelity simulation tools for predicting the dynamic response of IPWR systems under normal and off-normal conditions. Models exist for IPWR concepts spanning a range of thermal outputs, including designs similar to the Westinghouse IRIS, B&W mPower and NuScale reactor concepts [7].

Table III: SMR Operating Parameters

Parameter	**Value**
Reactor Thermal Output	530 MWt
Electric Output	180 MWe
Primary System Pressure	14.134 MPa (2050 psia)
Core Inlet Temperature	296.67 ˚C (566 ˚F)
Core Exit Temperature	321.67 ˚C (611 ˚F)
Core Flow Rate	13.608x10^{6} kg/hr (30 Mlbm/hr)
Steam Pressure	5.688MPa (825 psia)
Steam Temperature	299.44 ˚C (571 ˚F)
Feed Temperature	212.22 ˚C (414 ˚F)
Steam Flow Rate	9.53x10^{5} kg/hr (2.1Mlbm/hr)

1.3 Connection Points

The performance of the TES system is a strong function of the connection point to the secondary side of the IPWR. A typical main steam line configuration is illustrated in Figure 2. For plants incorporating Once Through Steam Generators (OTSG) the turbine control valve (TCV) acts as a pressure control valve to maintain Steam Generator pressure at a given set point. With this in mind, there are two options for bypassing steam to the TES system. Bypass can either be taken off the steam line at the pressure equalization header before the turbine control valves, or after the turbine control valves prior to entering the high pressure turbine. For the TES system design assumed here, it is desired to have roughly constant steam conditions since the shell side pressure in the Intermediate Heat Exchanger directly affects the TES fluid temperature leaving the IHX. This makes taking bypass steam from the pressure equalization header upstream of the turbine control valves the preferred operating mode. Steam conditions downstream of the TCVs are a strong function of the load profile. Taking bypass steam downstream of the turbine control valves could result in highly varying steam pressures and temperatures and result in unacceptably low IHX pressures.

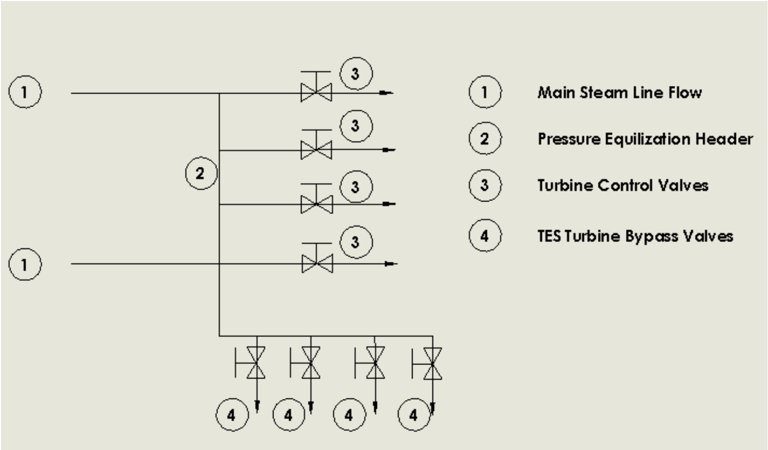

Figure 2: TES configuration with bypass taken prior to the Turbine Control Valves.

1.4 TES System Control

The TES system has four sets of valves used to control system parameters: auxiliary bypass valves, the TES flow control valve, the auxiliary control valve, and pressure relief valves.

The goal of the bypass flow controller is to provide bypass steam to the TES system at a rate sufficient to maintain the reactor at or near its nominal steady state value. The bypass valve controller generates an error signal based on the difference between measured bypass flow and a bypass flow demand signal. The bypass demand signal assumes the required bypass flow is proportional to the relative difference between the nominal full power turbine output and the instantaneous electric load plus a correction term (shim). The shim term modifies the demand signal such that reactor power is kept approximately constant.

$$Signal_{TBV} = \frac{\dot{m}_{Bypass_{Demand}}}{\dot{m}_{Bypass_{\mathrm{Ref}}}} - \frac{\dot{m}_{Bypass}}{\dot{m}_{Bypass_{\mathrm{Ref}}}} \tag{1}$$

$$\dot{m}_{Bypass_{Demand}} = \dot{m}_{\mathrm{nominal}} \frac{W_{Fullpower} - W_{load}}{W_{load}} + Shim_{TES} \tag{2}$$

$$Shim_{TES}^{t+\Delta t} = Shim_{TES}^{t} + \frac{K_{Shim}\dot{m}_{\mathrm{nominal}}\left(Q_{Rx_{ref}} - Q_{Rx}\right)\Delta t}{Q_{Rx_{ref}}} \tag{3}$$

Flow from the cold tank to the hot tank is via a TES flow control valve. The TES flow control valve operates off a three element controller where the first error signal is designed to maintain the TES fluid temperature leaving the Intermediate Heat Exchanger at some reference value. The second error signal is designed to roughly match the heat input into the TES fluid with the heat bypassed to the IHX.

$$Signal_{FCV} = G_1 Error_1 + G_2 Error_2 \tag{4}$$

$$Error_1 = \frac{T_{IHX_{Exit}} - T_{IHX_{Exitref}}}{T_{IHX_{Exitref}}} \tag{5}$$

$$\begin{aligned} Error_2 &= \frac{\dot{m}_{Bypass}}{\dot{m}_{Bypass_{\mathrm{Ref}}}} - \frac{\dot{m}_{TES}}{\dot{m}_{TES_{\mathrm{Ref}}}} \\ \dot{m}_{TES_{\mathrm{Ref}}} &= \frac{\dot{m}_{Bypass_{\mathrm{Ref}}}\left(h_{Steam} - h_f(\mathrm{P}_{IHX})\right)}{c_{p_{TES}}\left(T_{IHX_{\mathrm{Ref}}} - T_{CT}\right)} \end{aligned} \tag{6}$$

where $\dot{m}_{Bypass_{\mathrm{Ref}}}$ is the reference design bypass flow rate for the IHX.

The auxiliary control valve (ACV) maintains IHX hot well level. This valve operates on a three element controller based on the level of the IHX and the difference in mass flows into and out of the IHX as shown in equations (7)-(9) where G_1 and G_2 are error weighting gains.

$$\mathrm{Signal}_{\mathrm{ACV}} = G_1 E_1 + G_2 E_2 \tag{7}$$

$$E_1 = \text{Level-Level}_{\mathrm{Ref}} \tag{8}$$

$$E_2 = \dot{m}_{\mathrm{bypass}} - \dot{m}_{\mathrm{ACV}} \tag{9}$$

Pressure relief valves (PRV's) have been installed in the IHX to mitigate pressure increases. Should pressure reach an upper set point the valves will open according to equation (10) and will not close until the pressure falls below a lower set point.

$$Signal_{PRV} = \frac{P_{IHX} - P_{IHX_{\text{Setpoint}}}}{P_{IHX_{\text{Setpoint}}}} \qquad (10)$$

The only parameters directly controlled during charging mode operation of the TES system are the IHX exit temperature on the inner loop and the level in the IHX. All other variables including IHX pressure, tank levels, inner loop mass flow rate, and heat transfer across the IHX are determined from the mass, energy and momentum balances on the system.

A stop valve (not shown) is placed in the flow line between the cold tank and hot tank to ensure tank pressure and level stay below designated set points. Should either the pressure or level set points be exceeded the stop valve will close and TES fluid flow between the tanks will cease. A redundant control on level is that the volume of Therminol-66 in the system is less than the total volume of either tank.

2 RESULTS

To compare several different modes of operation, a 24-hour simulation was run for an electric load profile representative of a typical summer day in an area with mixed commercial and residential characteristics [9]. The load profile has been scaled such that the minimum load is approximately 60% of nominal full power. Time zero corresponds to midnight.

2.1 Load Follow Operation

The SMR is operating in Load Follow mode, where the reactor power is modulated to match the electric demand. As shown in Figures 3 and 4, the system is able to maneuver such that the turbine output is effectively identical to the electric demand, and the reactor power follows the load. For this simulation, a constant T_{ave} program was assumed with the corresponding control rod positions given in Figure 6. Four control banks are modeled. At the beginning of the maneuver, banks A-C are fully withdrawn, with D bank approximately 50% inserted. Over the course of the maneuver bank D moves to its full out position, and by the end of the transient has returned to its approximate starting point. Of additional interest is the steam pressure downstream of the TCV (Turbine Impulse Pressure). As stated previously, steam conditions at this location are a strong function of the load profile and create additional challenges if connections to the TES system are made at this point.

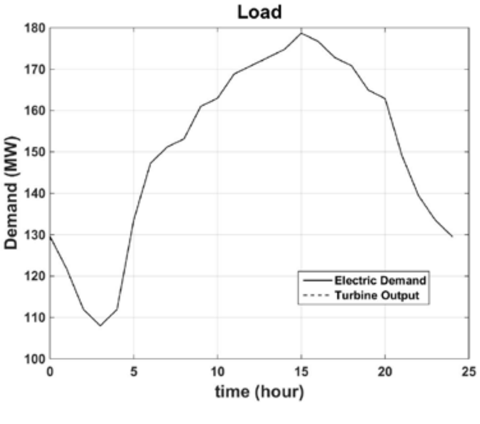

Figure 3: Turbine Output and Demand

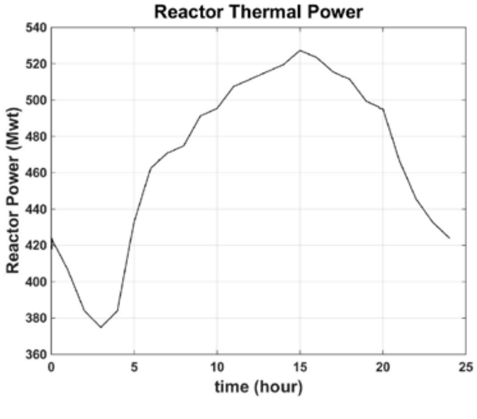

Figure 4: Reactor Power

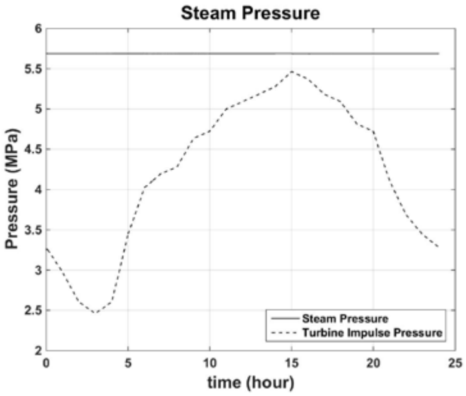

Figure 5: Steam Pressure

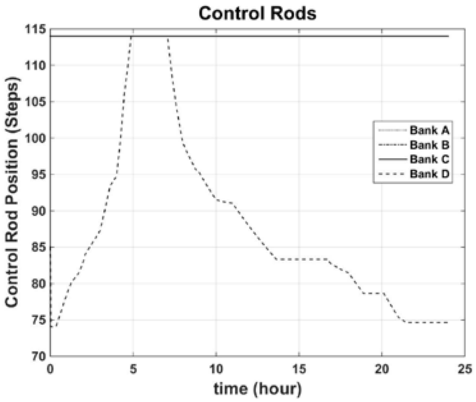

Figure 6: Control Rod Position

2.2 Reactor coupled with TES storage system operation

A 24-hour charging run was simulated with the TES system active. The same electric load profile as in the Load Follow case was assumed. As illustrated in Figures 7 and 8, the plant is able to maneuver such that the electric demand is satisfied while keeping reactor power effectively constant. As reactor power and T_{ave} were essentially constant, this maneuver could be executed without control rod movement. The corresponding bypass flow to the TES system is shown in Figure 9. As would be expected, the bypass flow rate is essentially the inverse of the load profile. The TES fluid flow rate is shown in Figure 10 and closely follows the bypass flow rate. Steam generator and turbine impulse pressure are essentially unchanged from the Load Follow simulations.

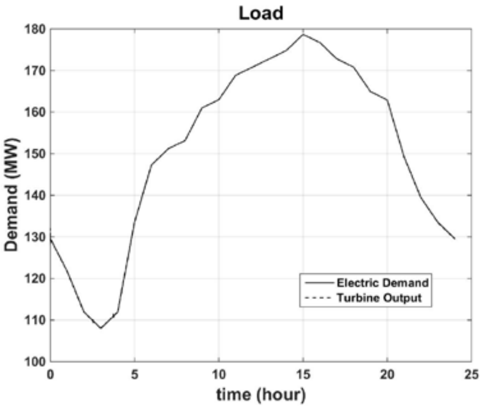

Figure 7: Turbine Output and Demand

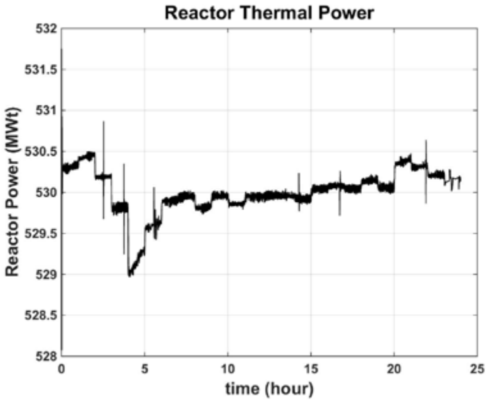

Figure 8: Reactor Power

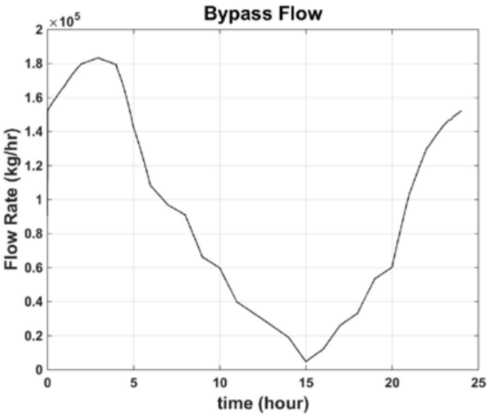

Figure 9: Bypass Flow into TES system

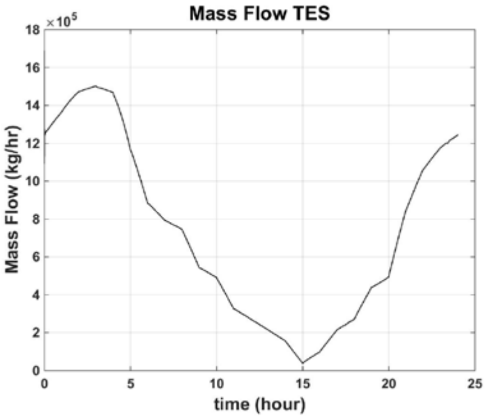

Figure 10: Flow of TES Fluid from Cold Tank to Hot Tank

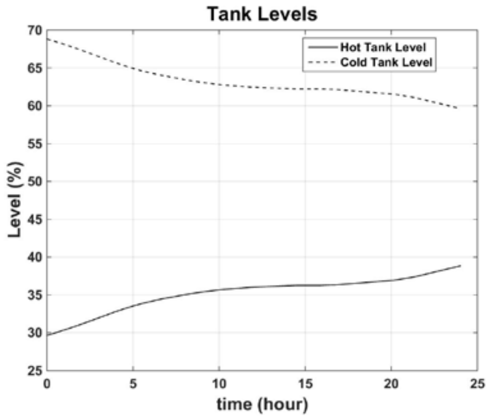

Figure 11: Hot and Cold Tank Levels

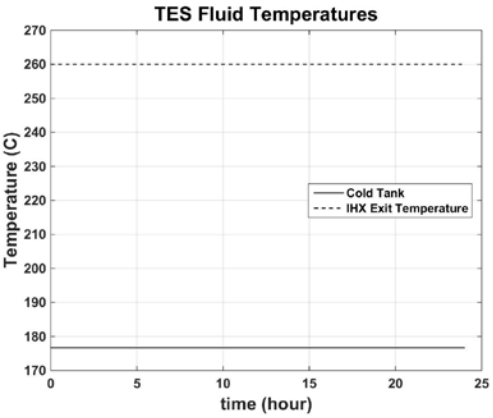

Figure 12: TES Temperatures

Figure 12 demonstrates that the flow controller for the TES flow control valve (FCV) is effective in keeping the IHX exit fluid temperature at its target value. The hot and cold storage tank levels are given in Figure 11. For the load profile considered here, the tanks have more than enough capacity to accommodate the excess thermal energy in the system.

2.3 Reactor coupled with TES storage system and intermittent renewables

An advantage of the TES system is the ability to accommodate the presence of intermittent energy sources on the grid, particularly solar energy penetration that can vary depending on time of day or cloud cover. To illustrate these effects the load profile was modified to reflect upwards of 40MWe installed solar capacity as shown in Figure 13 and Figure 14. Over the course of the simulation, turbine load is met while thermal power stays approximately constant as illustrated in Figure 15 and Figure 16. The response of other system parameters is similar to that shown previously for the typical summer day. The TES system has the capacity to charge for the full 24 hour run as tank levels go from 29% to 45%, shown in Figure 18.

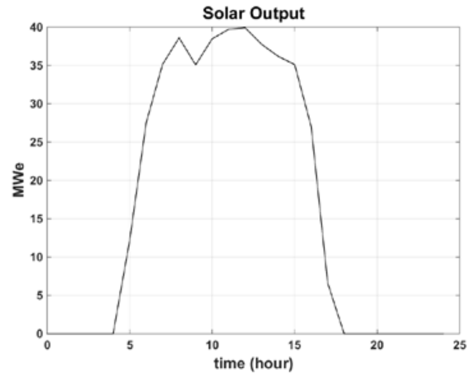

Figure 13: Typical Solar Output for a Summer Day

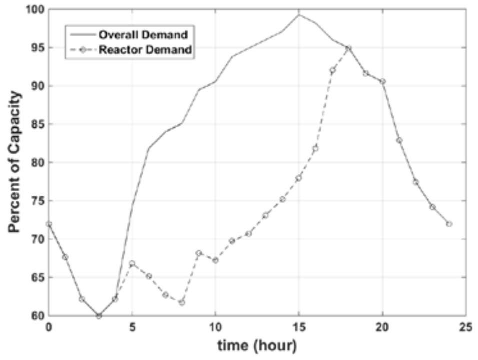

Figure 14: Demand Profiles of a Typical Summer Day with and without Solar

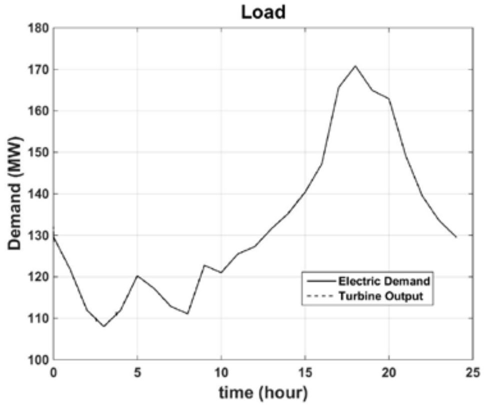

Figure 15: Turbine Load and Output

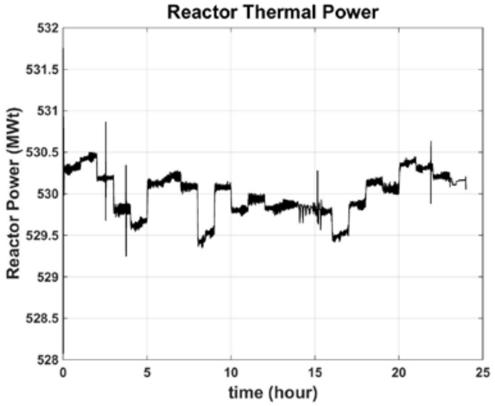

Figure 16: Reactor Power

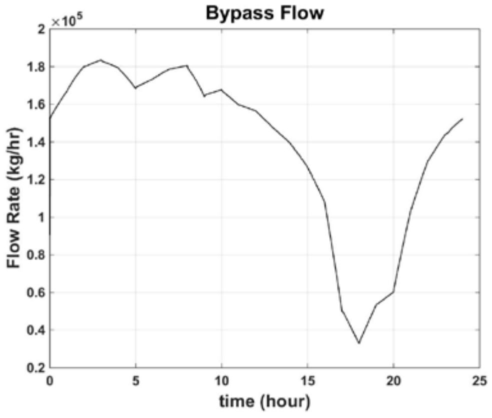

Figure 17: Auxiliary Bypass Flow

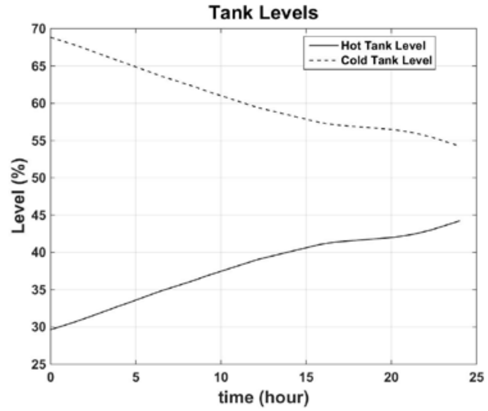

Figure 18: Hot and Cold Tank Levels

3 CONCLUSIONS

The results presented demonstrate the feasibility of using TES systems coupled to Small Modular Reactors to minimize power swings during periods of variable electric load. If SMRs are to be deployed in conjunction with intermittent power sources such as wind and solar, these load variations can be significant. Through the use of a sensible heat storage system, it has been shown thermal energy can be stored during periods of low demand, to be recovered at a later time for either electric generation or process heat applications. With the implementation of a TES system, decreases in capacity factor and increased stresses on plant components associated with load follow operation can be minimized, improving economic return over the lifespan of the reactor.

4 NOMENCLATURE

ACV	auxiliary control valve
Aux	auxiliary
c_p	specific heat
f	saturated liquid
FBV	flow bypass valve
FCV	flow control valve
G_1,G_2	gains
IHX	intermediate heat exchanger
m	mass
MWe	megawatts electric
OTSG	once through steam generator
P	pressure
ρ	density
PRV	pressure relief valve
ΔP	pressure drop
$\dot{Q}$	heat transfer rate
t	time
T	temperature
$T_{IHXexit}$	temperature at exit of IHX (tube side)
TBV	turbine bypass valve
TES	thermal energy storage

5 ACKNOWLEDGEMENTS

This material is based upon work supported under a Department of Energy, Office of Nuclear Energy, Integrated University Program Graduate Fellowship.

6 REFERENCES

1. S. BRAGG-SITTON, R. BOARDMAN, J. COLLINS, M. RUTH, O. ZINAMAN, C. FORSBERG. “Integrated Nuclear-Renewable Energy Systems: Foundational Workshop Report”. Idaho National Laboratory, INL/EXT-14-32857 Rev. 1 (2014).
2. D. INGERSOLL, C. COLBERT, Z. HOUGHTON, R. SNUGGERUD, J. GASTON, and M. EMPEY. "Can Nuclear Power and Renewables Be Friends?" *Proceedings of ICAPP* (2015): 3129-3137. Print.
3. K. POWELL, T. EDGAR. “Modeling and control of a solar thermal power plant with thermal energy storage”. *Chemical Engineering Science.* **138-145**, 71 (2012).

4. Solutia: Applied Chemistry, Creative Solutions, *Therminol 66: High Performance Highly Stable Heat Transfer Fluid.*
5. Solutia: Applied Chemistry, Creative Solutions, *Therminol 68: Highly Stable Low Viscosity Heat Transfer Fluid.*
6. Solutia, *Therminol 75: Synthetic, Aromatic, High-temperature Heat Transfer Fluid.*
7. Advances in Small Modular Reactor Technology Developments; A supplement to IAEA Advanced Reactors Information System (ARIS), IAEA (2014)
8. K. Frick, *Coupling and Design of a Thermal Energy Storage System for Small Modular Reactors*, Masters of Science Thesis, Department of Nuclear Engineering, North Carolina State University, 2016.
9. "Renewable Energy and Electricity," 20 June 2016. [Online]. Available: http://www.worldnuclear.org/information-library/energy-and-the-environment/renewable-energy-and-electricity.aspx. [Accessed 08 July 2016].